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The Residual Resistance Ratio of Pure Iron

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Metallurgy Division

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Abstract: The resistance at zero magnetic induction of iron specimens of varying impurity content has been determined by extrapolating the longitudinal magnetoresistance data taken at magnetic fields above saturation. Such resistance values may then be used to determine a modified residual resistance ratio (*RRR*), which is shown to be a more appropriate index of purity for ferromagnetic metals than that obtained with resistances measured in zero applied magnetic field.

INTRODUCTION

For most metals, a very sensitive index of purity is the residual resistance ratio (*RRR*) defined by $R_{300}/R_{4.2}$, where R_{300} and $R_{4.2}$ are the electrical resistances at 300° and 4.2°K, respectively. However, this ratio cannot be used as a measure of purity for ferromagnetic metals mainly because the value of $R_{4.2}$ for a ferromagnetic metal contains magnetoresistive contributions, even in zero applied field, which are comparable in magnitude to those of impurity scattering (1). A magnetoresistive term is also present at 300°K, but it has a relatively small effect on *RRR* because of the increased size of the phonon scattering contribution to the resistance.

A modified form of *RRR*, more appropriate for characterizing the impurity content of ferromagnetic metals, may be obtained by an examination of the nature and implications of magnetoresistance data. At 4°K, the electrical resistance of ferromagnetic metals, as a function of applied longitudinal field, is found to decrease initially, to pass through a minimum, and then to increase monotonically beyond technical saturation (1). To explain the low-field resistance variations, two mechanisms (1,2), both based upon the presence of Weiss domains, have been postulated. Either of these mechanisms would be operative at zero applied magnetic field and would make a large contribution to the residual resistivity measured at zero applied field.

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To explain the low-field data, Sudovtsov and Semenenko (2) have proposed a resistive term which is related to diffuse electron scattering from domain walls and which should be considered in addition to the "normal" magnetoresistance. As a magnetic field is applied, domain walls are swept out, and this contribution goes to zero. Berger and de Vroomen (1), on the other hand, suggest that both the low- and high-field magnetoresistance behavior are due to the same basic process, *i.e.*, both are due to the field **B** acting on the conduction electrons (3). In the absence of an applied magnetic field, the electrons are nevertheless moving in the effective field within the individual domains, which is equal to the spontaneous magnetization $4\pi M$ (22 kgauss for iron). According to Berger and de Vroomen, the random domain orientations present in zero applied field result in the internal local field being aligned approximately parallel to the current in some domains, and approximately perpendicular in other domains. As a small longitudinal magnetic field is applied, longitudinal domain alignment occurs, and preponderantly longitudinal magnetoresistance results. Since transverse magnetoresistance is larger than longitudinal magnetoresistance, the average resistance of the sample decreases. This latter effect is also considered by Semenenko and Sudovtsov, but they conclude that it is not as important as domain wall scattering.

Regardless of which of the above models is appropriate for explaining the low-field magnetoresistance behavior, it is clear that, for ferromagnetic metals, the value of the resistance at zero applied field contains a magnetoresistive contribution, and thus is not appropriate for use in characterizing the purity of the metal. Nor

TABLE 1
Iron Specimens Used in Magnetoresistance Measurements

Specimen	Preparation	Diameter (mm)	Length Between Potential Leads (cm)
Fe-1	U.H.V. zone refining	irregular (≈4)	4
Fe-2*	Annealed, but not refined. From same stock as Fe-1.	5	3.5
Fe-3	Single crystal prepared by Materials Research Corp.	2	1.5

*For specimen Fe-2, two runs were made. Run 2 used a new set of contacts placed approximately, but not exactly, in the same places as those used in run 1.

can one use the value of the resistance at the position of the minimum since this value contains a term related to the "normal" longitudinal magnetoresistance which, in turn, arises from the internal field of each domain acting on the conduction electrons. In order to obtain a value of the resistance which does not contain contributions related to the ferromagnetic nature of the metal, it is necessary to examine the variation of the resistance with applied magnetic field beyond the region of technical magnetic saturation. Here, the longitudinal magnetoresistance can be attributed entirely to "normal" longitudinal magnetoresistance, such as is exhibited by nonferromagnetic metals. Since **B** is the field acting on the conduction electrons (3), it is possible to obtain a resistance value, which in principle contains no magnetoresistive contributions, by extrapolating the high-field data back to $B=0$. Using this value for $R_{4.2}$ and the usual value of R_{300}, a value of $RRR|_{B=0}$ can be obtained which should be an index of the purity of the specimens and which should be comparable to values of RRR obtained for similar metals having no intrinsic magnetization.

EXPERIMENTAL TECHNIQUES

To obtain and evaluate $RRR|_{B=0}$ for ferromagnetic metals, the longitudinal magnetoresistance of three iron specimens of varying degrees of purity was measured at room and liquid helium temperatures using standard potentiometric procedures. These samples are described in Table 1. At liquid helium temperature, data were taken as a function of applied longitudinal magnetic fields up to 5 koe and of specimen currents of 10 amp and lower. Samples Fe-1 and Fe-2 were prepared from "99.999% pure," 5-mm-diam iron rod supplied by the United Mineral and Chemical Co. Sample Fe-1 was electron-beam, float-zone refined in a vacuum of 10^{-9} torr. Two passes were made. Sample Fe-2 was annealed at approximately 400°C in a vacuum of 7×10^{-8} torr but was not further refined. For sample Fe-2, two separate resistance measurements were made. In the second measurement, a new set of electrical contacts were placed at approximately the same places as those used in the first measurement. Sample Fe-3 was a 2-mm-diam, high-purity single crystal supplied by the Materials Research Corporation.

RESULTS AND DISCUSSION

Figure 1 is a plot showing the normalized resistivity change $[R(H)-R_0]/R_0 = \Delta\rho/\rho$ *versus* the applied longitudinal magnetic field at 4.2°K; R_0 is the resistance at zero applied field. Initially, as **H** is increased, $\Delta\rho/\rho$ decreases rapidly. After the initial decrease, $\Delta\rho/\rho$ varies only slightly with applied field for values of $H = 800$ oe or higher. In this initial region, the behavior may be explained on the basis of either domain wall scattering or the domain alignment mechanism proposed above. The slight increase in resistivity with applied field beyond the region where the specimen is ferromagnetically saturated is the "normal" longitudinal magnetoresistance due directly to the total internal field **B**.

Although marked differences (probably due to crystal texture) are noted between specimens Fe-1 and Fe-3 below saturation, their behavior above

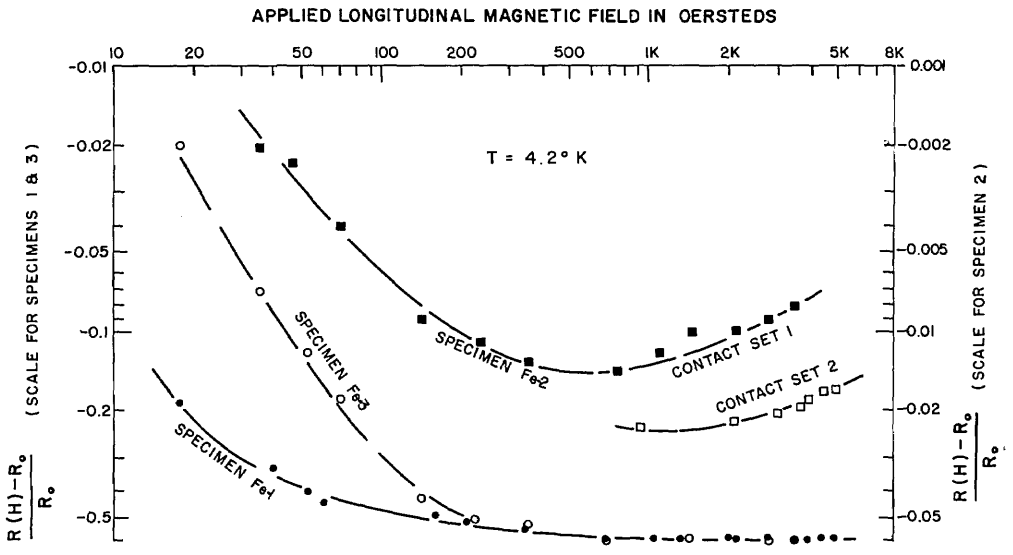

Fig. 1 — Normalized resistivity change for three iron specimens at 4.2°K in an applied longitudinal magnetic field

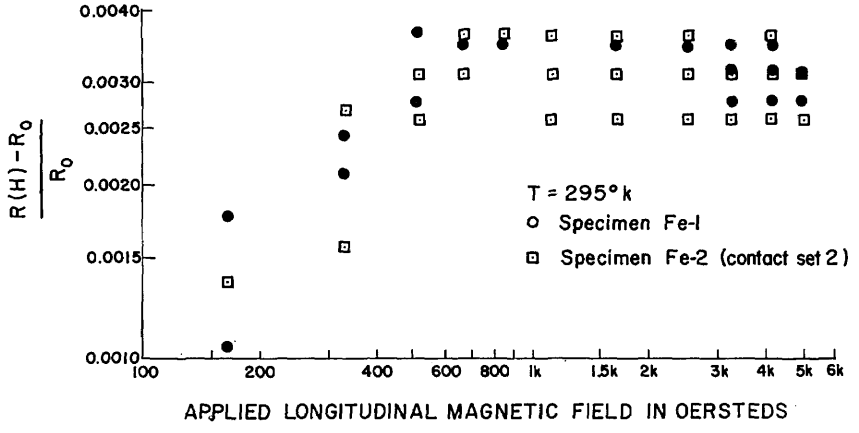

Fig. 2 — Normalized resistivity change for three iron specimens at room temperature in an applied longitudinal magnetic field

saturation is quite similar. The magnitude of the initial resistivity change appears to be very dependent upon purity. The absolute magnitude of $(\Delta\rho/\rho)_{min}$ for the purified specimens Fe-1 and Fe-3 is 25 to 50 times as large as that for the nonpurified specimen Fe-2 and is also larger than the values noted by other investigators (2). Further study may show that the magnitude of $(\Delta\rho/\rho)_{min}$ is a satisfactory indication of purity; however, it is felt that the more fundamental method is that of the extrapolation to zero induction and the calculation of $RRR|_{B=0}$.

Figure 2 is a plot showing the normalized resistivity change $[R(H)-R_0]/R_0 = \Delta\rho/\rho$ *versus* the applied longitudinal field at 295°K. The magnetoresistance at 295°K is orders of magnitude smaller than that at 4°K. In addition, it is always positive and does not appear to be significantly dependent

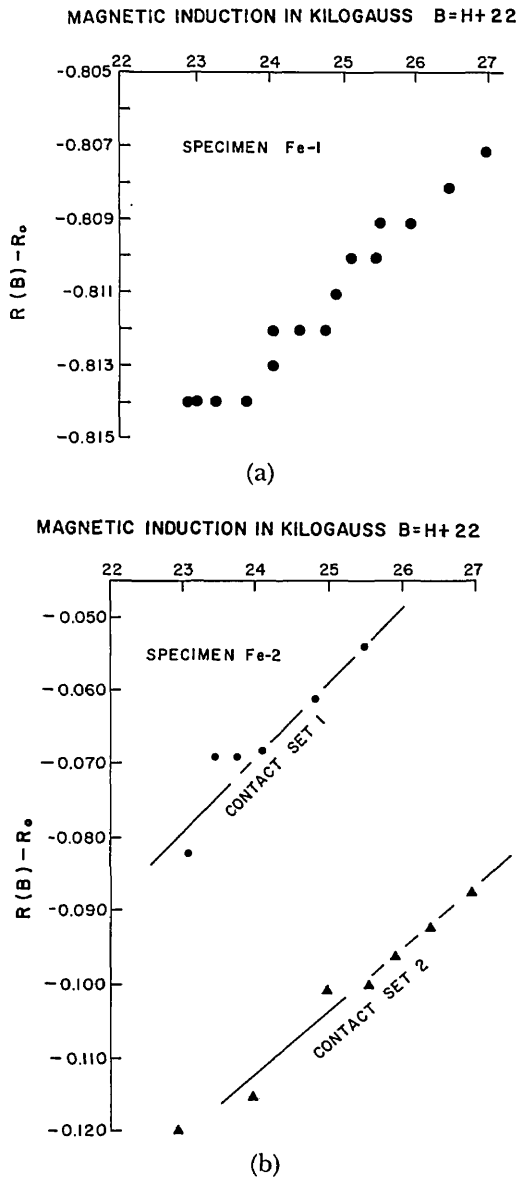

Fig. 3 — The variation of resistance with magnetic induction for specimen (a) Fe-1 and (b) Fe-2 at 4.2°K used in extrapolation to $B=0$

on impurity. This data clearly shows that it is not necessary to perform the extrapolation to $B=0$ to obtain a room-temperature resistance value for use in calculating $RRR|_{B=0}$.

Figures 3(a) and 3(b) show the variation of $[R(B) - R_0]$ with B at applied longitudinal fields greater than those necessary to saturate the specimen ($H \gtrsim 1$ koe). The results of a linear extrapolation of this data have been used to obtain R for $B=0$ and $T=4$°K.* For these values, true RRR's ($RRR|_{B=0}$) have been calculated for specimens Fe-1 and Fe-2. These results are shown in Table 2 and are compared with RRR values obtained in the normal manner. Uncertainty in the extrapolation to $B=0$ is mainly responsible for the large uncertainties in the $RRR|_{B=0}$ values. These uncertainties were so large for specimen Fe-3 (due to the small physical dimensions of the specimen and the limited amount of heat that could be dissipated into the liquid helium bath) that a meaningful value of $RRR|_{B=0}$ could not be obtained for this specimen.

TABLE 2
Comparison of the Residual Resistance Ratios RRR by Extrapolation to $B=0$ and by the Usual Method

Specimen	$RRR\|_{B=0}$	RRR
Fe-1	630±30	231±5
Fe-2 {contact set 1	{32±5	{30.5±0.5
Fe-2 {contact set 2	{40±5	{37.9±0.5
Fe-3	Not obtained (see text)	242±6

For sample Fe-1, which was zone refined, a value of 231 was determined for RRR, the residual resistance ratio measured in the usual fashion. For the sample Fe-2, RRR was found to be 30-38. Although these values clearly indicate that Fe-1 is of higher purity than Fe-2, the differences found for the RRR of the two samples were not a good indication of their relative purities. Using the extrapolation procedure given above, Fe-1 is found to have a value of $RRR|_{B=0}=630$ (or 605 using square-law extrapolation), while that for Fe-2 has not changed significantly and is 32-40 (or 31-19 using square-law extrapolation). It is felt that the values of $RRR|_{B=0}$ provide an indication of purity that is superior to the standard determination of RRR, which always gives values of 300 or less for iron specimens of known high purity (1). The values of $RRR|_{B=0}$ obtained for the purified specimens are more compatible with the values of RRR obtained for similar, but nonferromagnetic, metals.

*For ferromagnetic metals, the magnetoresistance at low temperatures and above saturation appears to vary as B^n, where $1 \leq n \leq 2$. Our data do not give a clear indication as to the power law dependence. Using a square-law extrapolation, the resultant resistance ratios are within the experimental error quoted in Table 2 for samples Fe-1 and Fe-2.

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13. ABSTRACT

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